

Dynamics of Strangeness Production and Strange Matter Formation *

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1 Introduction

We want to draw the attention to the dynamics of a (finite) hadronizing quark matter drop. Strange and anti-strange quarks do not hadronize at the same time for a baryon-rich system¹. Both the hadronic and the quark matter phases enter the strange sector $f_s \neq 0$ of the phase diagram almost immediately, which has up to now been neglected in almost all calculations of the time evolution of the system. Therefore it seems questionable, whether final particle yields reflect the actual thermodynamic properties of the system at a certain stage of the evolution. We put special interest on the possible formation of exotic states, namely strangelets (multi-strange quark clusters). They may exist as (meta-)stable exotic isomers of nuclear matter². It was speculated that strange matter might exist also as metastable exotic multi-strange (baryonic) objects (MEMO's³). The possible creation — in heavy ion collisions — of long-lived remnants of the quark-gluon-plasma, cooled and charged up with strangeness by the emission of pions and kaons, was proposed in^{1,4,5}. Strangelets can serve as signatures for the creation of a quark gluon plasma. Currently, both at the BNL-AGS and at the CERN-SPS experiments are carried out to search for MEMO's and strangelets, e. g. by the E864, E878 and the NA52 collaborations^{9,10}.

2 The model

We adopt a model⁵ for the hadronization and space-time evolution of quark matter droplet. We assume a first order phase transition of the QGP to hadron gas. The expansion of the QGP droplet is described in a hybrid-like model, which takes into account equilibrium as well as nonequilibrium features of the

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process by the following two crucial, yet oversimplifying (and to some extent controversial) assumptions: (1) the plasma sphere is permanently surrounded by a thin layer of hadron gas, with which it stays in perfect equilibrium (Gibbs conditions) during the whole evolution; in particular the strangeness degree of freedom stays in chemical equilibrium because the complete hadronic particle production is driven by the plasma phase. (2) The nonequilibrium radiation is incorporated by a time dependent freeze-out of hadrons from the outer layers of the hadron phase surrounding the QGP droplet. During the expansion, the volume increase of the system thus competes with the decrease due to the freeze-out. The global properties like (decreasing) S/A and (increasing) f_s of the remaining two-phase system then change in time according to the following differential equations for the baryon number, the entropy, and the net strangeness number of the total system:

$$\begin{aligned}\frac{d}{dt}A^{tot} &= -\Gamma A^{HG} \\ \frac{d}{dt}S^{tot} &= -\Gamma S^{HG} \\ \frac{d}{dt}(N_s - N_{\bar{s}})^{tot} &= -\Gamma (N_s - N_{\bar{s}})^{HG},\end{aligned}\tag{1}$$

where $\Gamma = \frac{1}{A^{HG}} \left(\frac{\Delta A^{HG}}{\Delta t} \right)_{ev}$ is the effective (‘universal’) rate of particles (of converted hadron gas volume) evaporated from the hadron phase. The equation of state consists of the bag model for the quark gluon plasma and a mixture of relativistic Bose–Einstein and Fermi–Dirac gases of well established strange and non-strange hadrons up to 2 GeV in Hagedorn’s eigenvolume correction for the hadron matter¹. Thus, one solves simultaneously the equations of motion (1) and the Gibbs phase equilibrium conditions for the intrinsic variables, i.e. the chemical potentials and the temperature, as functions of time.

3 Strangelet distillation at low μ/T

In⁶ it was shown that large local net-baryon and net-strangeness fluctuations as well as a small but finite amount of stopping can occur at RHIC and LHC. This can provide suitable initial conditions for the possible creation of strange matter in colliders. A phase transition (e. g. a chiral one) can further increase the strange matter formation probability. In⁶ it was further demonstrated with the present model that the high initial entropies per baryon do not hinder the distillation of strangelets, however, they require more time for the evaporation and cooling process.

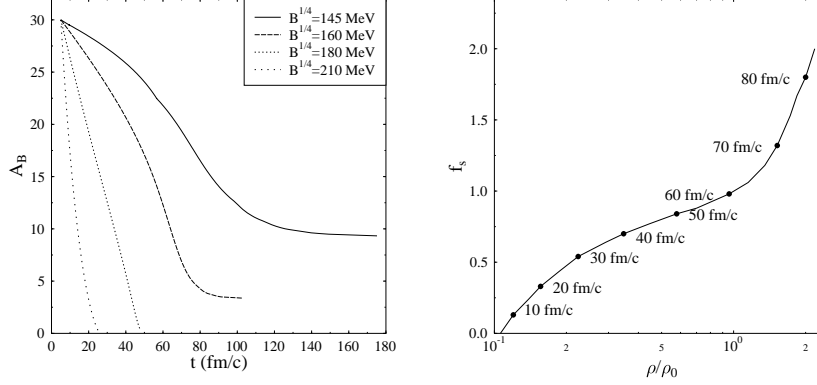


Figure 1: Time evolution of the baryon number for a QGP droplet with $A_B^{\text{init}} = 30$, $S/A^{\text{init}} = 200$, $f_s^{\text{init}} = 0.7$ and different bag constants (left). Evolution of a QGP droplet with baryon number $A_B^{\text{init}} = 30$ for $S/A^{\text{init}} = 200$ and $f_s^{\text{init}} = 0$. The bag constant is $B^{1/4} = 160$ MeV. Shown is the baryon density and the corresponding strangeness fraction (right).

Fig. 1 (left) shows the time evolution of the baryon number for $S/A^{\text{init}} = 200$ and $f_s^{\text{init}} = 0.7$ for various bag constants. For $B^{1/4} < 180$ MeV a cold strangelet emerges from the expansion and evaporation process, while the droplet completely hadronizes for bag constants $B^{1/4} \geq 180$ MeV (for $B^{1/4} = 210$ MeV hadronization proceeds without any significant cooling of the quark phase, although the specific entropy S/A decreases by a factor of 2 from 200 to only 100). The strangeness separation works also in these cases, and leads to large final values of the net strangeness content, $f_s \gtrsim 1.5 - 2$. However, then the volume of the drop becomes small, it decays and the strange quarks hadronize into Λ -particles and other strange hadrons. For even higher bag constants $B^{1/4} \approx 250$ MeV neither the baryon concentration effect nor strangeness distillery occurs (Fig. 4).

Fig. 1 (right) shows the evolution of the two-phase system for $S/A^{\text{init}} = 200$, $f_s^{\text{init}} = 0$ and for a bag constant $B^{1/4} = 160$ MeV in the plane of the strangeness fraction vs. the baryon density. The baryon density increases by more than one order of magnitude! Correspondingly, the chemical potential rises as drastically during the evolution, namely from $\mu^i = 16$ MeV to $\mu^f > 200$ MeV. The strangeness separation mechanism drives the chemical potential of the strange quarks from $\mu_s^i = 0$ up to $\mu_s^f \approx 400$ MeV. Thus, the thermodynamical and chemical properties during the time evolution are quite different from the initial conditions of the system.

Fig. 1 illustrates the increase of the baryon density in the plasma droplet

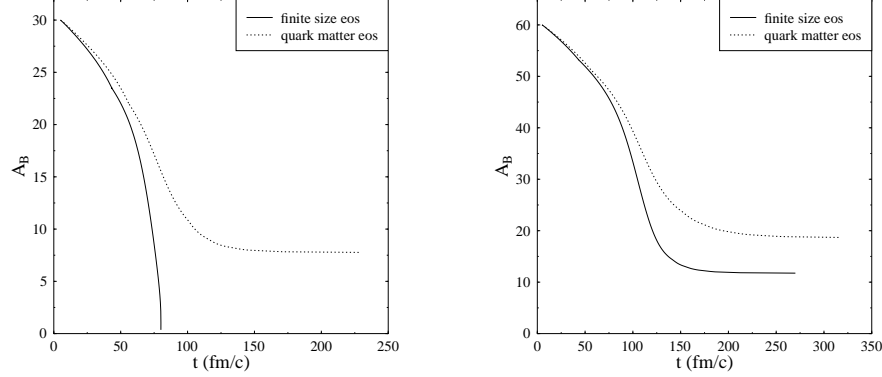


Figure 2: Time evolution of the net baryon number of a QGP droplet, calculated with (full line) and without (dashed line) finite size corrections to the quark matter equation of state. The initial conditions are $f_s^{\text{init}} = 0$ and $S/A^{\text{init}} = 200$. The bag constant is $B^{1/4} = 145$ MeV.

as an inherent feature of the dynamics of the phase transition (cf. ⁷). The origin of this result lies in the fact that the baryon number in the quark-gluon phase is carried by quarks with $m_q \ll T_C$, while the baryon density in the hadron phase is suppressed by a Boltzmann factor $\exp(-m_{\text{baryon}}/T_C)$ with $m_{\text{baryon}} \gg T_C$. Mainly mesons (pions and kaons) are created in the hadronic phase. More relative entropy S/A than baryon number is carried away in the hadronization and evaporation process⁵, i.e. $(S/A)^{HG} \gg (S/A)^{QGP}$. Ultimately, whether $(S/A)^{HG}$ is larger or smaller than $(S/A)^{QGP}$ at finite, nonvanishing chemical potentials might theoretically only be proven rigorously by lattice gauge calculations in the future. However, model equations of state do suggest such a behaviour, which would open such intriguing possibilities as baryon inhomogeneities in ultrarelativistic heavy ion collisions as well as in the early universe.

4 Finite size effects

The bag model equation of state for infinite quark matter is certainly a very rough approximation. Regarding finite size effects the leading correction to the quark matter equation of state is the curvature term. For massless quarks the volume term of the grandcanonical potential suffers the following modification (including the gluon contribution)⁸:

$$\Omega_C = \left(\frac{1}{8\pi^2} \mu_q^2 + \frac{11}{72} T^2 \right) C \quad (2)$$

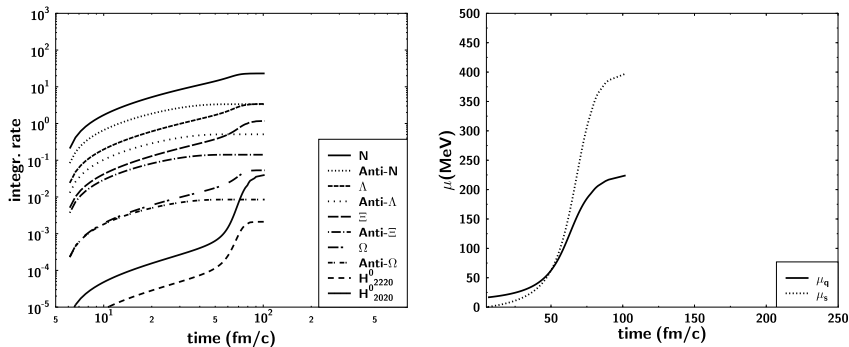


Figure 3: Integrated rates of particles, evaporated out of a hadronizing QGP droplet as functions of time (left) and the corresponding (strange) quark chemical potential (right). The initial conditions are $f_s^{\text{init}} = 0$, $S/A^{\text{init}} = 200$ and $A_B^{\text{init}} = 30$. The bag constant is $B^{1/4} = 160$ MeV, the mass of the H^0 is varied between $m = 2020$ MeV and $m = 2220$ MeV.

with $C = 8\pi R$ being the curvature of the spherical bag surface. From this one can easily derive all thermodynamic quantities and study the evolution of the two-phase system QGP/hadron gas in the above described model. It shows that even in the case of a favourable bag constant $B^{1/4} = 145$ MeV a quark blob with an initial net baryon number of $A_B^{\text{init}} = 30$ will completely hadronize — in contrast to the calculation with the unmodified equation of state (Fig. 2). Of course, the difference between the dynamics according to the two equations of state is reduced for larger systems. Still, it can be speculated that shell effects may allow for the formation of rather small strangelets which are stable. Moreover, the introduction of a more realistic hadronic equation of state (e. g. with the help of a relativistic mean field theory including adequate interactions for strange hadrons³) might modify this pessimistic picture again.

5 Particle rates from the hadronizing plasma

Enhanced production of strange particles in relativistic nuclear collisions has received much attention recently^{9,10}. In particular thermal models have been developed and applied^{11,12} to explain (strange) particle yields and to extract the characteristic thermodynamic properties of the system (a few macroscopic parameters) from them. In our model the picture of a sudden hadronization which is supposed in these studies is only one possible outcome. Under more general assumptions the observed particle rates have to be put in relation to the whole time evolution of the system.

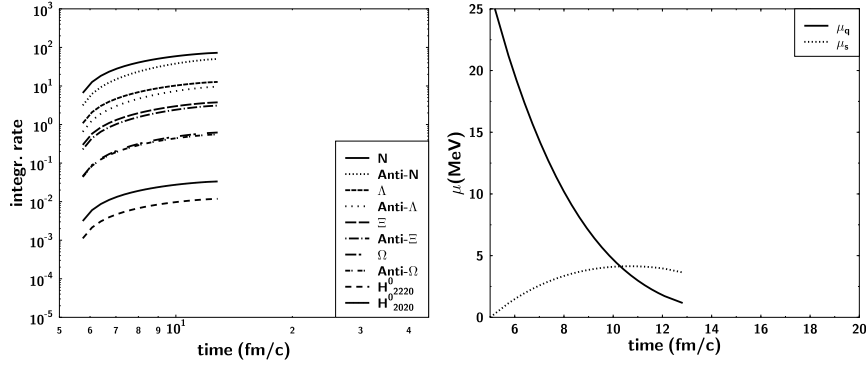


Figure 4: Integrated rates of particles, evaporated out of a hadronizing QGP droplet as functions of time (left) and the corresponding (strange) quark chemical potential (right). The initial conditions are $f_s^{\text{init}} = 0$, $S/A^{\text{init}} = 200$ and $A_B^{\text{init}} = 30$. The bag constant is $B^{1/4} = 250$ MeV, the mass of the H^0 is varied between $m = 2020$ MeV and $m = 2220$ MeV.

The integrated particle rates and the quark chemical potentials as functions of time have been calculated for two different scenarios: In Fig. 3 the results are plotted for a bag constant of $B^{1/4} = 160$ MeV which is favorable for the strangeness distillation. In Fig. 4 a very high bag constant of $B^{1/4} = 250$ MeV is used. This results in a very rapid (and complete) hadronization without significant cooling. Obviously, in the first case the particle rates reflect the massive changes of the chemical potentials during the evolution (which is the result of the strangeness distillation process). Note that e. g. the Λ 's are emitted mostly at the late stage, whereas the $\bar{\Lambda}$'s stem almost exclusively from the early stage. The $\bar{\Lambda}/\Lambda$ ratio is therefore not a meaningful quantity (if one takes it naively), since the two yields represent different sources! For the other choice of the bag constant the present model renders more or less the picture which is claimed by 'static' thermal models: the plasma fireball decomposes very fast into hadrons (watch the different time scales of Figs. 3 and 4) and the quark chemical potentials stay low compared to the temperature. Time dependent rates of the hypothetical H^0 Dibaryon are also shown in Figs. 3 and 4. This particle is introduced to the hadronic resonance gas with its appropriate quantum numbers and two different assumed masses. It appears that the distillation mechanism gives rise to H^0 yields of the same order as the $\bar{\Omega}$'s (Fig. 3) if the mass is $m_{H^0} \approx 2020$ MeV. For the high bag constant the H^0 yields are much more suppressed as compared to the strange (anti-)baryons. The absolute yields of the H^0 do not change much, since the system emits the particles at significantly higher temperature (due to the high bag constant).

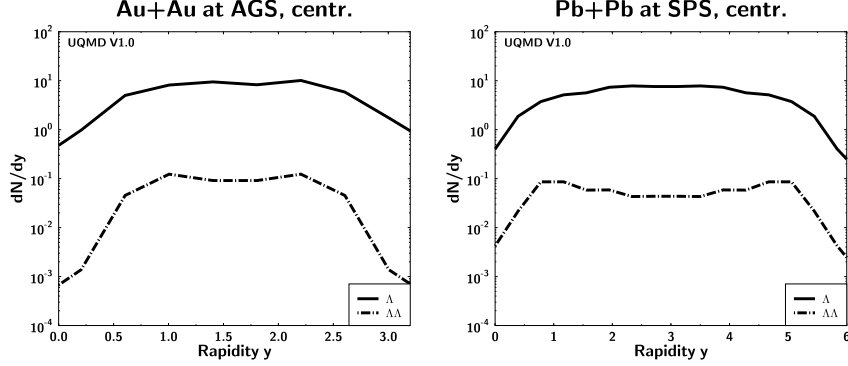


Figure 5: Rapidity distributions of hyperons and Λ - Λ -clusters calculated with URQMD1.0 β plus a clustering procedure according to the Wigner-function method. Shown are the spectra for central collisions of Au+Au at 10.7 GeV (left) and Pb+Pb at 160 GeV (right).

6 Hyper-cluster formation in a microscopic model

We now apply the Ultrarelativistic Quantum Molecular Dynamics 1.0 β ^{13,14}, a semiclassical transport model, to calculate the abundances of strange baryon-clusters in relativistic heavy ion collisions. The model is based on classical propagation of hadrons and stochastic scattering (s channel excitation of baryonic and mesonic resonances/strings, t channel excitation, deexcitation and decay). In order to extract hyper-cluster formation probabilities the Λ pair phase space after strong freeze-out is projected on the assumed dilambda wave function (harmonic oscillator) via the Wigner-function method as described in¹⁵. According to the weak coupling between Λ 's in mean-field calculations³ we assume the same coupling for $\Lambda\Lambda$ -cluster as for deuterons¹⁵.

In Fig. 5 the calculated rapidity distributions of hyperons and $\Lambda\Lambda$ -clusters are shown for central reactions of heavy systems at AGS and SPS energies. The multiplicities of Λ 's plus Σ^0 's in inelastic p+p reactions are 0.088 ± 0.003 at 14.6 GeV/c and 0.234 ± 0.005 at 200 GeV/c with the present version of the model. These numbers are given to assess the absolute yields in A+A collisions. The hyperon rapidity density stays almost constant when going from AGS to SPS energies, the dN/dy of the hyper-clusters even drops slightly at midrapidity. This is due to the higher temperature which gives rise to higher relative momenta and therefore a reduced cluster probability. The $\Lambda/\Lambda\Lambda$ ratio is approximately 100, which can be compared to the Λ/H^0 ratios which result from the expanding quark gluon plasma (see last section).

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